Inequality, Survival to Adulthood, and the Growth Drag of Pollution

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ABSTRACT

We theoretically investigate the interrelationship between economic inequality and the exposure to pollutants during the course of economic development. Environmental pollution adversely affects children's probability to survive to adulthood, reduces thus parental expenditures on child quality and increases the number of births necessary to achieve a desired family size. Children's exposure to environmental pollution is determined by economic inequality because wealthier households live in cleaner areas which shapes then differences in the level of human capital per child. This is the key mechanism through which environmental conditions impose a growth drag on the economy. Our theory provides a candidate explanation for: (i) The hump-shaped evolution of child mortality ratios between cleaner and more polluted areas during the course of economic development, and (ii) the observed positive correlation between inequality and the concentration of pollutants at the local level.

1. INTRODUCTION

The Industrial Revolution induced an immense increase in both economic activity and environmental pollution. While the latter adversely affected children's health status and parents' incentives to invest in child quality, the second phase of the Industrial Revolution was marked by massive investments in children's education inducing a decline in fertility rates and sustained economic growth (see f.e. Galor, 2011). Simultaneously, the decline in fertility rates was associated with a decline in child mortality rates that implied a lower number of births necessary to achieve a desired family size leaving eventually more resources available for expenditures on child quality (Strulik, 2004, 2008).

In this paper, we argue that the transition to reduced fertility rates and increasing parental expenditures on education per child requires public policies that mitigate the adverse impact of production on children's health. These policies, however, require the support of pivotal social groups. Agents' willingness to support these policies, in turn, is predominantly driven by their exposure to pollutants and their disposable incomes. The consideration of this dimension is crucial since wealthier households live in cleaner areas (see for example Tiebout, 1956, and Roback, 1982) and face therefore lower child mortality rates.[1] Consequently, richer households exhibit lower fertility rates and invest more in education which reinforces the impact of inequality on differential fertility (de la Croix and Doepke, 2003). A lower exposure to pollutants reduces ceteris paribus richer agents' willingness to pay for tax-financed abatement measures. Poorer agents, on the other hand, may exhibit an even lower willingness to pay if their incomes are sufficiently low forcing them to put a stronger emphasis on subsistence needs rather than on environmental quality. In earlier stages of economic development, the adverse effects of pollution would then be highest if the pivotal social group is poor and has no political power to tax richer agents. In more advanced stages of economic development even poorer agents' disposable incomes are sufficiently high allowing them to support tax-financed abatement measures, potentially exceeding the preferred abatement level of the rich which are less exposed to pollutants.

The contribution of this paper to the literature is twofold: (i) on a theoretical level we analyze how inequality shapes the preferences for tax-financed abatement measures and parental incentives to invest in their children's education. (ii) By doing so this paper provides along an empirical dimension a candidate explanation for a) the hump-shaped evolution of child mortality ratios between areas that are subject to different degrees of environmental pollution as illustrated in Figure 1, and b) the positive cross-country correlation between economic inequality and pollution at the local level, see Figure 2(a).

We apply an overlapping generations (OLG) model with endogenous fertility and a hierarchy of needs due to subsistence consumption. The probability to survive to adulthood depends positively on the stage of economic development and disposable incomes of households but is adversely affected by environmental pollution. An increase in the probability to survive to adulthood reduces the number of births necessary to achieve a desired family size and leaves more resources available for educating the surviving children. Thus, economic development may be conducive for children's survival probabilities, but may also generate via pollution an adverse impact on children's probability to survive to adulthood. The exposure to pollutants determined by economic inequality triggers again children's probability to survive to adulthood and the willingness of parents to invest in education.

[1] Exposure to pollution depends thus on economic wealth although medical knowledge about the impact of pollution on health was limited at earlier stages of economic development. The "miasma" theory (Deaton, 2003) stressed the relevance of a clean environment for health.

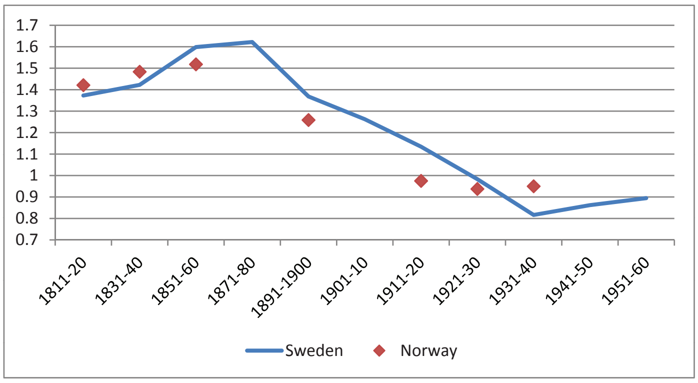

Figure 1: Ratio of child mortality rates in urban and rural regions (Bairoch, 1988)

This is the key mechanism of our model through which environmental conditions may impose a growth drag on the economy.

Only a few papers analyze the interaction between environmental aspects and health within an OLG framework (Mariani, Perez-Baharona, and Raffin, 2010; Varvarigos, 2010). Moreover, these papers relate longevity and environmental quality to poverty traps, while this paper emphasizes the adverse impact of pollution on children's health and the resulting prospects for economic growth.[2] Likewise, endogenous population dynamics has been linked to our best knowledge to the depletion of non-renewable resources only (see for example Bretschger, 2013; Peretto and Valente, 2015; Schaefer, 2014), but not to environmental pollution. On a conceptual level, this paper builds on seminal works by Glomm and Ravikumar (1992) which is the workhorse in the literature related to OLG models with endogenous human capital formation and de la Croix and Doepke (2003, 2004) who established an analytical framework regarding the interaction between fertility, education and inequality. Our research is also related to a seminal paper by Ehrlich and Lui (1991) who analyze parents investments in their children to achieve old-age support and emotional compensation from them. We abstract from intergenerational trade but take account for inequality and endogenous improvements in child mortality in response to tax-finance abatement measures. With respect to the relationship between health and fertility this paper is also related to Strulik (2004, 2008).[3]

The nexus between inequality, health, and residential exposure to pollutants has been documented impressively by economic historians (Szreter, 1997). Urban populations often had no access to clean water. Fresh water was used for commercial purposes while the new entrepreneurial class saw no point in spending money for sanitation and sewage treatment plants which had no obvious commercial benefit (Hassan, 1985). Pollution from smoke and other factory discharges contaminated the atmosphere and the environment.

[2]Related to Mariani et al. (2010) is Ono and Maeda (2001) and Jouvet et al. (2010).

[3]Strulik, Prettner and Prskawetz (2013) also offer an OLG model with endogenous education and fertility but focus on historical and future trends in R&D-based growth.

Schwartz (2004) demonstrates that especially children tend to be more vulnerable as a result of early life exposure to pollutants leading directly to increased child mortality or indirectly through changes in birth outcomes that translate into higher mortality risks later in life. In developed countries, this effect is significant but less pronounced compared to earlier stages of economic development (see Chay and Greenstone, 2003, Currie and Neidell, 2005, and Currie et al., 2009).[4] The initially adverse impact of economic development on children's survival probabilities is impressively documented by Figure 1. In the nineteens century, child mortality rates in cities relative to rural areas increased in Sweden and Norway rapidly to a 1.6 ratio at the end of the century and experienced a decline to a ratio smaller than one during the first quarter of the 20th century only.[5] The hump-shaped pattern applies also for richer agents which moved to the periphery of cities compared to poorer groups of the society living in the cities close to the production centers and emission sources. In this paper, we explain the hump-shaped evolution of child mortality differentials by differences in the residential exposure to pollutants. Poorer households living in more polluted areas exhibit lower human capital endowments compared to richer households living in less polluted areas. Thus poorer households invest less in child quality while their children face a lower probability to survive to adulthood. Consequently, mortality differentials increase if production and pollution increase. In later phases of economic development, the mortality differentials close again because even poorer households exhibit higher incomes and increase their expenditures on health and nutrition. This process will be reinforced by the implementation of tax-financed abatement measures. Figure 2(b) and (c) support the arguments of our theory, in the sense that pollution interferes with the quality quantity trade-off; see also Figure 2(d) which illustrates the quality quantity trade-off as such.

The remainder of the paper is organized as follows: In Section 2, we introduce our overlapping generations framework. In Section 3, we discuss inequality with respect to agents' human capital endowments and with respect to their exposure to pollutants. Section 4 performs numerical experiments analyzing the impact of inequality on mortality differentials and of pollution on inequality. Moreover, we explore there the interaction between inequality, exposure to pollutants and preferences for tax-financed abatement measures. Finally, Section 5 provides a summary and concludes.

2. THE MODEL

2.1. Human Activities and Pollution

In this setting, time is discrete, indexed by t and ranges from 0 to ∞. A large number of firms produce aggregate output (Y_t) using a constant returns to scale technology of Cobb-Douglas type, where K_t denotes aggregate physical capital and H_t^Y aggregate effective

[4] For an extensive overview, see Graff Zivin and Neidell (2013).

[5] Bairoch (1988) discusses very similar developments for other European countries. Szreter (1997) documents that rapid urbanization associated with the Industrial Revolution induced higher mortality rates in cities than in the countryside, and a decline in overall life expectancy. In addition Hainse (2004) and Komlos (1998) provide evidence for increased morbidity over the same period of time.

[6] Particulate matter concentrations refer to fine suspended particulates less than 10 microns in diameter (PM10) that are capable of penetrating deep into the respiratory tract and causing significant health damage. Data for countries and aggregates for regions and income groups are urban-population weighted PM10 levels in residential areas of cities with more than 100,000 residents. The estimates represent the average annual exposure level of the average urban resident to outdoor particulate matter. The state of a country's technology and pollution controls is an important determinant of particulate matter concentrations (see World Bank Indicators, 2013).

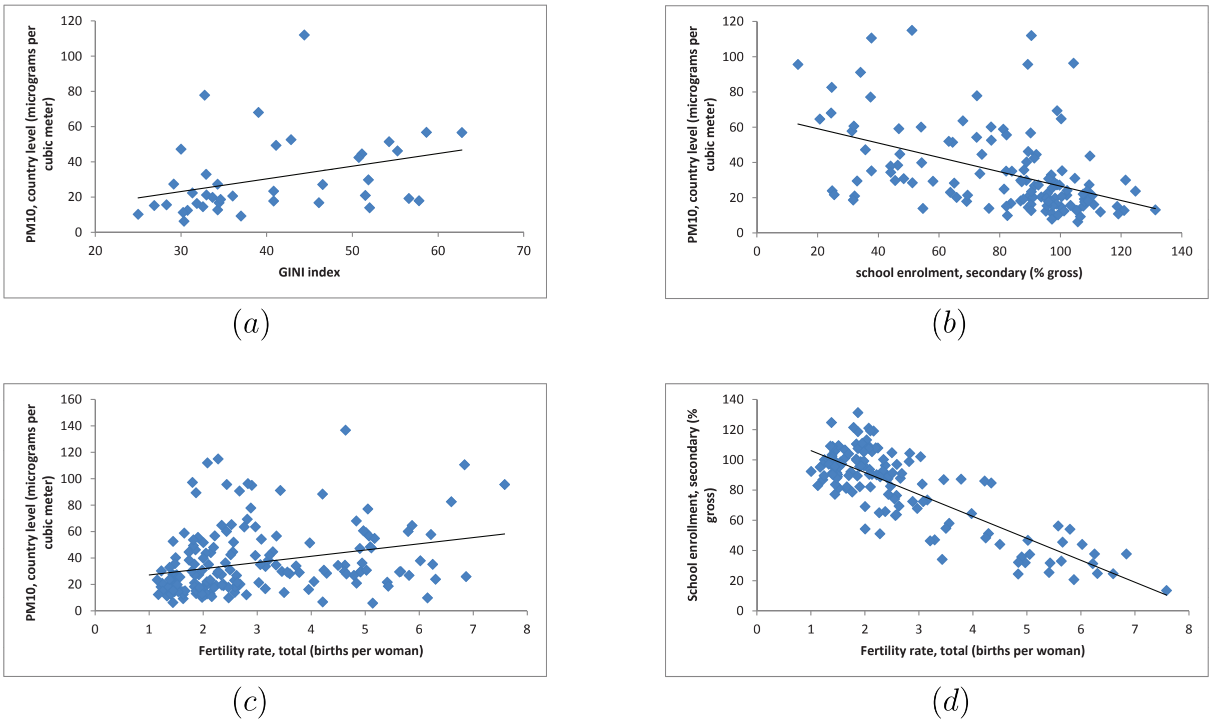

Figure 2: Cross-country correlations between (a) inequality and pollution (particulate matter[6]), (b) pollution and schooling, (c) pollution and fertility, and (d) schooling and fertility. Source: World Bank: World Development Indicators, 2013)

labor employed in production, such that

$$Y_t = A \cdot (K_t)^{\alpha}(H_t^Y)^{1-\alpha}, \tag{1}$$

with $A > 0$, $\alpha \in (0, 1)$.
Production generates emissions (E_t) which may be attenuated by abatement measures (M_t) financed by a proportional tax, $0 \leq \tau_t < 1$, on households' income. Ordas Criado et al. (2011) speak in this context about defensive expenditures devoted to activities that reduce the emissions of the production sector. In order to allow for balanced growth and zero abatement measures, emissions in period t are given by

$$E_t = (b_2 \frac{Y_t}{H_t} - b_3 \frac{M_t}{H_t}) = (b_2 - b_3\tau_t)\frac{Y_t}{H_t}, \qquad b_2, b_3 > 0, \tag{2}$$

where b_2 reflects the impact of production on the environment, b_3 the productivity of abatement measures, and H_t aggregate human capital. Eq.(2) allows for balanced growth and captures at the same time the notion that it becomes increasingly difficult to abate as the economy develops. Note that the tax rate (τ_t) is endogenous, not necessarily positive, and dependent on the preferences of a pivotal agent (the political decision problem will be introduced in Section 2.3). Moreover, the environment is adversely affected by population size ($\mathcal{N}_t$) which captures the adverse effect of population density and congestion on the environment, an effect which is not necessarily reflected by aggregate output since the latter depends on aggregate effective labor supply. Finally, the environment regenerates at a constant rate ($0 \leq b_1 \leq 1$) per period of time. Therefore, the stock of pollutants evolves in spirit of John and Pecchenino (1994) over time according to

$$P_{t+1} = (1 - b_1)P_t + E_t + b_4\mathcal{N}_t = (1 - b_1)P_t + (b_2 - b_3\tau_t)\frac{Y_t}{H_t} + b_4\frac{\mathcal{N}_t}{H_t}, \tag{3}$$

with $b_4 > 0$ reflecting the adverse impact of population on the environment.[7]

2.2. Households

Consider an economy populated by overlapping generations. Each generation consists of a large number of households indexed by i which differ in terms of their levels of human capital and their exposure to pollutants introduced further below. Households live for two periods: childhood and adulthood. All economically relevant decisions are made in the adult period of life. Adult households care about the number of children (n_t^i) they wish to raise and the quality per child reflected by their health status (s_t^i) as well as the level of human capital per child (h_{t+1}^i). Hence, parents do not care about their descendants utility but receive a *warm glow* of giving (Andreoni, 1989). Moreover, parents' expenditures on children are motivated by the desire for having "higher quality" children (Becker, 1960). Looking at estimates of values for children's health indicates that parents behave considerably altruistic with respect to their children's health (Agee and Crocker, 2001; Liu et al., 2000; Dickie and Ulery, 2001).

h_{t+1}^i depends on education (e_t^i), the parental level of human capital (h_t^i) and the level of human capital per teacher in the education sector (h_t^T)

$$h_{t+1}^i = (\varepsilon + e_t^i)^{\eta}(h_t^i)^{\nu}(h_t^T)^{1-\nu}. \tag{4}$$

$\eta \in (0,1)$ reflects the impact of education on the level of human capital. $\nu \in (0,1)$ denotes the intergenerational transmission of human capital or the intergenerational persistence between parental human capital and the level of human capital per child (see for example Glomm and Ravikumar, 1992, and de la Croix and Doepke, 2003;2004). The parameter $\varepsilon > 0$ will allow for $e_t^i = 0$.

The health status (s_t^i) determines the probability to survive childhood (π_t^i), i.e $\pi_t^i = \pi_t^i(s_t^i)$ with $\frac{\partial \pi_t^i}{\partial s_t^i} > 0$ if $\pi_t^i < 1$. Building on Strulik (2008), s_t^i is determined by an *intrinsic component* (d_t^i) which is endogenous to the household and an *extrinsic component* ($\bar{\pi}_t$) which is exogenous to the household, i.e. $s_t^i = s_t^i(d_t^i, \bar{\pi}_t)$ such that $\pi_t^i = \pi_t^i(d_t^i, \bar{\pi}_t)$.[8] The intrinsic component is steered by parental expenditures on health and nutrition (d_t^i). The extrinsic component ($\bar{\pi}_t$), in turn, is positively affected by the state of economic development reflected by the average stock of human capital (h_t^m), but adversely affected by environmental pollution (P_t), i.e. $\bar{\pi}_t = \bar{\pi}_t(h_t^m, P_t)$. We therefore depart from Strulik (2008) along two dimensions: 1) The extrinsic component is determined by the willingness to support tax-financed abatement measures. 2) The components driving $\bar{\pi}_t$ depend on economic inequality.[9]

[7]Thus a balanced growth path with a constant Y_t/H_t-ratio is characterized by a non-increasing pollution stock, if the growth rate of the population is lower than the growth rate of human capital which is empirically for advanced economies a plausible scenario. Usually the literature and also this paper analyzes the regulation of a single pollutant and abstracts from complementary or substitutive relationships between different kinds of pollutants. An economically reasonable steady state requires the compatibility of economic growth with non-declining environmental quality such that in general pollution approaches a finite steady state level (see for example Ordas Criado et al., 2011; Brock and Taylor, 2005 and 2010; Bovenberg and Smulders, 1995).

[8]This disaggregation of survival probabilities stems from biology, for example the intrinsic component is nutrition while the extrinsic component is reflected by the natural environment, let's say temperature (see Strulik, 2008 for further details).

[9]A growing body of literature has analyzed the hump-shaped relationship between the provision of health care and endogenous growth within the context of OLG frameworks (Kuhn and Prettner, 2016; Schneider and Winkler, 2010; Aisa and Pueyo, 2004;2006). We consider private expenditures on health and nutrition and emphasize the importance of tax-financed abatement measures.

The relationship between the extrinsic and the intrinsic component of children's health status is formalized as follows (we denote steady state values by an asterisk):
The extrinsic survival component ($\bar{\pi}_t$) is increasing and concave in the stage of economic development reflected by the average level of human capital (h_t^m). In contrast $\bar{\pi}_t$ is declining and convex in the level of pollutants (P_t) such that

(a) $\bar{\pi}_t = \bar{\pi}(h_t^m, P_t)$, with $\frac{\partial \bar{\pi}(h_t^m, P_t)}{\partial h_t} > 0$, $\frac{\partial^2 \bar{\pi}(h_t^m, P_t)}{\partial h_t^2} < 0$, $\frac{\partial \bar{\pi}(h_t^m, P_t)}{\partial P_t} < 0$ and $\frac{\partial^2 \bar{\pi}(h_t^m, P_t)}{\partial P_t^2} < 0$. Moreover,

(b) $\bar{\pi}_t(0, P_t) = 0$, $\lim_{P_t \to \infty} \bar{\pi}_t(h_t^m, P_t) = 0$, $\bar{\pi}_t(h_t^m, 0) < \infty$ and $\lim_{h_t^m \to \infty} \bar{\pi}_t(h_t^m, P_t) = \bar{\pi}_* < 1$.[10]

The health status (s_t^i) determines the survival probability (π_t^i) of a child born in household i via parental expenditures on health and nutrition (d_t^i), the intrinsic component. The productivity of d_t^i is improved by the extrinsic survival component ($\bar{\pi}_t$), if d_t^i exceeds a critical level $\tilde{d} \geq 1$

$$s_t^i = \lambda (d_t^i)^{\bar{\pi}^0}, \text{ if } d_t^i \leq \tilde{d} \tag{5}$$
$$s_t^i = \lambda (d_t^i)^{\bar{\pi}_t}, \text{ if } d_t^i > \tilde{d}, \tag{6}$$

where $\lambda > 0$ represents a productivity parameter and $\bar{\pi}^0 > 0$ is a constant parameter, with $0 < \bar{\pi}^0 < \bar{\pi}_t < 1 \; \forall \; t$. Moreover, $s_t^i(0, \bar{\pi}_t) = 0$. Children's probability to survive to adulthood is determined by $\pi_t^i = \min\{1; s_t^i(d_t^i, \bar{\pi}_t)\}$, such that

$$\pi_t^i(s_t^i) \in [0, 1]. \tag{7}$$

In addition to n_t^i and children's quality, adult agents care about their own level of consumption (c_t^i) above subsistence needs ($\bar{c}$) and the amount of bequests per child (b_t^i). Agents experience a disutility from the future level of pollution (P_{t+1}) such that preferences of a member i of generation t that is born in $t-1$ are specified as

$$u_t^i = \ln(c_t^i - \bar{c}) + \gamma \ln(n_t^i q_t^i) + \rho \ln b_t^i - \mu P_{t+1}, \tag{8}$$

with $q_t^i = (s_t^i)(h_{t+1}^i)^\beta$ and $\beta, \gamma, \mu, \rho, \bar{c} > 0$.[11]
As, $\pi_t^i = \pi_t^i(s_t^i)$, the appearance of $n_t^i q_t^i$ in the parental utility function implies that parents derive utility out of the number of surviving offspring, such that agents are forced to increase fertility whenever child mortality is high in order to achieve their desired family size and vice versa. If $\pi_t^i = 1$ parents derive utility out of an increasing health status of their children.[12]
The presence of P_{t+1} in the parental utility function captures some degree of altruism

[10] $\bar{\pi}_* < 1$ is necessary to assure reasonable solutions, in the sense that the weight of child quality is smaller than the weight of quantity in the parental utility function.

[11] Pollution generating a negative externality on agents' welfare has been analyzed within a Ramsey framework by van der Ploeg and Withagen (1991), Gradus and Smulders (1993), Beltratti (1996) or Xepapadeas (1997, Chapter 3). For further details see also Xepppadeas (2005). For endogenous growth models see for example Grimaud (1999).

[12] Note that $\gamma \ln(n_t^i q_t^i) = \gamma[\ln(n_t^i s_t^i) + \beta \ln(h_{t+1}^i)]$. In order to capture morbidity effects, we could also associate the health status of children explicitly to the productivity in human capital accumulation and labor productivity when adult. Further below we will see, however, that health improvements will increase human capital accumulation, such that the implementation of morbidity would not yield any further insights but increase the notational complexity.

with respect to the preservation of the environment for the next generation. We omit P_t in the parental utility function for convenience since it would not alter the optimization problem with respect to τ_t in the political process, because τ_t can only affect P_{t+1} but never P_t, see Eq. (3).[13]

Denote post-tax variables by "ˆ", the budget constraint of an agent i endowed with one unit of time, human capital (h_t^i), and assets ($b_{t-1}^{\prime i}$) reads as

$$\hat{y}_t^i = (\hat{w}_t h_t^i z + \hat{w}_t h_t^T e_t^i + b_t^i + d_t^i) n_t^i + c_t^i, \qquad \tau_t \in [0,1), \tag{9}$$

with $\hat{y}_t^i = (1-\tau_t)(w_t h_t^i + R_t b_{t-1}^{\prime i})$. w_t and R_t represent the wage rate per effective unit of labor and the return on capital.

Child rearing costs are captured by: first, forgone wage earnings ($\hat{w}_t h_t^i z n_t^i$), with $0 < z < 1$ denoting the time share necessary to raise one child to adulthood. Second, expenditures for education ($\hat{w}_t h_t^T e_t^i n_t^i$), where education is provided by an educational sector employing teacher equipped with human capital h_t^T. Third, expenditures on health and nutrition (d_t^i), and the level of bequests per child (b_t^i). The subsequent lemma summarizes households' optimal decisions - the proof can be found in the Online-Appendix.

Lemma 1 (Households' decisions)

Adult agents maximize lifetime utility as given by (8) subject to the budget constraint (9), and the evolution of human capital per child (4), while ignoring their impact on the evolution of the aggregate pollution stock. Denote by $x_t^i = \frac{h_t^i}{h_t^T}$ household i's level of human capital relative to h_t^T, then there exists a time varying threshold level of relative human capital

$$\tilde{x}_t = \frac{(1-\bar{\pi}_t)\gamma - \rho}{\gamma\beta\eta z}\,\varepsilon, \tag{10}$$

implying that $e_t^i = 0$, if $x_t^i \leq \tilde{x}_t$ or $e_t^i > 0$, if $x_t^i > \tilde{x}_t^i$, where $\frac{\partial \tilde{x}_t}{\partial \bar{\pi}_t} < 0$. Optimal decisions of household i read

(i) if $x_t^i > \tilde{x}_t$ and thus $e_t^i > 0$:

$$c_t^i = \frac{1}{1+\gamma}[\hat{y}_t^i + \gamma\bar{c}], \tag{11}$$

$$n_t^i = \frac{\gamma}{1+\gamma}\frac{\hat{y}_t^i - \bar{c}}{\hat{w}_t[h_t^i z + h_t^T e_t^i] + b_t^i + d_t^i}, \tag{12}$$

$$e_t^i = \frac{\gamma\beta\eta z x_t^i - (\gamma(1-\bar{\pi}_t) - \rho)\varepsilon}{\gamma(1-\beta\eta-\bar{\pi}_t) - \rho}, \tag{13}$$

$$d_t^i = \frac{\gamma\bar{\pi}_t(z - \frac{\varepsilon}{x_t^i})}{\gamma(1-\beta\eta-\bar{\pi}_t) - \rho}\hat{w}_t h_t^i, \tag{14}$$

$$b_t^i = \frac{\rho(z - \frac{\varepsilon}{x_t^i})}{\gamma(1-\beta\eta-\bar{\pi}_t) - \rho}\hat{w}_t h_t^i, \tag{15}$$

with $\gamma(1-\beta\eta-\bar{\pi}_t) - \rho > 0$.[14]

[13] Constant marginal disutility from pollution assures analytical tractability.

[14] The non-negativity constraint $\gamma(1-\beta\eta-\bar{\pi}_t) - \rho > 0$ is a common feature in models dealing with the quality-quantity trade-off: the weight of utility attached to the pure presence of children, γ, should exceed the weight of children's quality components in the parental utility function.

(ii) if $x_t^i \leq \tilde{x}_t$ and thus $e_t^i = 0$:

$$c_t^i = \frac{1}{1+\gamma}[\hat{y}_t^i + \gamma\bar{c}], \tag{16}$$

$$n_t^i = \frac{\gamma}{1+\gamma}\frac{\hat{y}_t^i - \bar{c}}{\hat{w}_t h_t^i z + b_t^i + d_t^i}, \tag{17}$$

$$b_t^i = \frac{\rho z}{\gamma(1-\bar{\pi}_t)-\rho}\hat{w}_t h_t^i, \tag{18}$$

$$d_t^i = \frac{\bar{\pi}_t z}{\gamma(1-\bar{\pi}_t)-\rho}\hat{w}_t h_t^i, \tag{19}$$

with $\gamma(1-\bar{\pi}_t)-\rho > 0$.

Households spend a fraction $\frac{1}{1+\gamma}$ of their post-tax income on consumption. The remaining part ($\frac{\gamma}{1+\gamma}$) is spent on child rearing. Fertility (n_t^i) is positively related to disposable incomes, but it is negatively related to forgone wage earnings per child ($zw_t h_t^i$), negatively associated to expenditures on child quality as captured by education (e_t^i), expenditures on health and nutrition (d_t^i), and the level of bequests per child (b_t^i). All these variables depend, for their part, positively on the level of parental relative human capital (x_t^i), and positively on the extrinsic component of children's survival probability ($\bar{\pi}_t$). The fact that the children's quality vector depends on parental relative human capital endowments allows us to study the evolution of the income dynamics by focusing on the evolution of x_t^i, only. The dependence of the quality vector on $\bar{\pi}_t$ implies that favorable environmental conditions raise the number of surviving children and reduce the desired level of fertility. As a consequence, more resources are available for education, nutrition and bequests.
$e_t^i > 0$ requires that parents' relative human capital stock (x_t^i) exceeds the critical threshold level $\tilde{x}_t$ as determined by (10). As a novel feature of our model, $\tilde{x}_t$ is time varying, declining in the extrinsic survival component ($\bar{\pi}_t$) and dependent on the preference to support tax-financed abatement measures. Thus a high pollution stock lowers child quality itself and increases $\tilde{x}_t$. Everything else equal, a lower pollution stock implies that parents with a lower x_t^i are now able to invest in eduction. If $x_t^i \leq \tilde{x}_t$ it follows that $e_t^i = 0$ and fertility is at the highest feasible value while b_t^i and d_t^i reach their lowest feasible values, see Lemma 1, item (ii).
At the beginning of the second period of life (adulthood), bequests of children that didn't survive to adulthood are equally redistributed within the family among the surviving offspring. Thus, wealth per adult at the beginning of period $t+1$ is

$$b_t'^i = \frac{b_t^i}{\pi_t^i}. \tag{20}$$

Now several points are worth being noticed: (i) for low levels of income, agents devote relatively more resources to consumption in order to cover subsistence needs while expenditures for fertility and child quality are low. During earlier stages of economic development this mechanism is reenforced by a low h_t^m and thus a low $\bar{\pi}_t$. Consequently, probabilities to survive to adulthood are low. Especially the critical threshold ($\tilde{x}_t$) is relatively high such that depending on the distribution of human capital only few households invest in education for their offspring. Hence, income gains at this stage of economic development are channeled towards an increase in fertility while the incentives to invest in child quality are low. (ii) Agents characterized by $x_t^i > \tilde{x}_t$ are willing to invest in education for their offspring and contribute, by doing so, to a slow increase in the average stock of human capital (h_t^m). In this early phase of economic development, capital accumulation fueled by bequests constitutes the major source of aggregate output growth. The increase in h_t^m enhances the extrinsic survival probability of children ($\bar{\pi}_t$), while the increase in production depletes environmental quality reflected by an increase in P_t. Thus, the increase in production induces an offsetting effect on $\bar{\pi}_t$. (iii) The increase in incomes allows for higher expenditures on health and nutrition enhancing c.p. children's prospects to survive to adulthood. Thus population growth may increase. Ultimately, the risk not to survive to adulthood plays a declining role as the economy develops eventually accelerated by the implementation of abatement measures. In view of declining mortality risks, parents reduce fertility in order to achieve their desired family size and allocate more resources towards child quality. Hence, population growth peaks, declines towards its steady state value and follows the for industrialized countries well documented hump-shaped pattern. The level of fertility and the pace of its decline depend on inequality and pollution.

2.3. Pollution abatement

We now introduce the endogenous emergence of abatement measures during the course of economic development by implementing a simple and in the literature on income distribution and institutions widely spread political process. The government sets a tax rate $0 \leq \tau_t < 1$ that maximizes a pivotal agent's (p) lifetime utility (8) given her optimal decisions as specified by Lemma 1 and by recognizing the evolution of the pollution stock (3). In an idealized democracy, we should consider the median-voter as the decisive agent. If, in turn, the political system is biased towards the rich or the poor (Benabou, 1996; Acemoglu, 2009), the median voter should be considered as a theoretical benchmark, rather. Whether the position of the pivotal agent in the income distribution matters for the implementation of pollution abatement, depends on the existence of subsistence consumption, i.e. $\bar{c} > 0$ - for a poof, see the Online-Appendix.

Proposition 1 (Preferred tax rate)
The government maximizes lifetime utility (8) of a pivotal agent (p) given optimal decisions as specified by Lemma 1 and the evolution of the pollution stock as defined by (3), such that

$$\max_{0 \leq \tau_t^p < 1} u_t^p \to \tau_t^p. \tag{21}$$

(i) If $\bar{c} > 0$ the preferred tax rate of the pivotal agent reads

$$\tau_t^p = \frac{(2y_t^p - \bar{c})b_3\mu Y_t - [1 + \gamma(\bar{\pi}_t + \rho)y_t^p H_t] - \sqrt{\Psi}}{2b_3\mu y_t^p Y_t}, \tag{22}$$

with $\Psi = [1 + \gamma(\bar{\pi}_t + \rho)]^2 (y_t^p)^2 H_t^2 + 2b_3\mu\bar{c}y_t^p H_t Y_t[1 + \gamma(2 - \bar{\pi}_t - \rho)] + b_3^2\mu^2\bar{c}^2 Y_t^2 > 0$ since $2 - \bar{\pi}_t - \rho > 0$ under reasonable parameter restrictions. Moreover, the preferred tax rate is increasing in income, y_t^p, but declines in the level of subsistence needs, $\bar{c}$, i.e. $\frac{\partial \tau_t^p}{\partial y_t^p} > 0$ and $\frac{\partial \tau_t^p}{\partial \bar{c}} < 0$. Furthermore, $\tau_t^p = 0$, if $y_t^p \leq \tilde{y}_t$, with $\tilde{y} = \frac{\bar{c}[-\gamma(1-\rho-\bar{\pi}_t)H_t - b_3\mu Y_t]}{[1+\gamma(\bar{\pi}_t+\rho)]H_t - b_3\mu Y_t} > 0$, if $\frac{H_t}{Y_t} < \frac{b_3\mu}{\gamma(1-\bar{\pi}_t-\rho)}$.

(ii) If $\bar{c} = 0$ the preferred tax rate reads as

$$\tau_t^{p,\bar{c}=0} = 1 - \frac{1 + \gamma(\bar{\pi}_t + \rho)}{b_3\mu}\frac{H_t}{Y_t} \tag{23}$$

and is independent from the level of income of the pivotal agent, i.e. $\frac{\partial \tau_t^p}{\partial y_t^p} = 0$*, such that* $\tau_t = \tau_t^i = \tau_t^{p,\bar{c}=0}$ *for all* i*. Moreover,* $\tau_t = 0$*, if* $\frac{H_t}{Y_t} < \frac{b_3 \mu}{1+(\bar{\pi}_t+\rho)}$.

(iii) For $\bar{c} \geq 0$*, i.e. disregarded the existence of subsistence consumption, capital accumulation increases the preferred tax rate, while human capital accumulation reduces the preferred tax rate, such that* $\frac{\partial \tau_t^p}{\partial K_t} > 0$ *and* $\frac{\partial \tau_t^p}{\partial H_t} < 0$*.*

Due to the existence of subsistence consumption ($\bar{c} > 0$), the level of the tax rate (τ_t^p) depends positively on the level of the pivotal agent's income (y_t^p), see item (i). Thus environmental preferences are subject to a hierarchy of needs, in the sense that richer agents prefer more abatement. On the other hand richer agents live in less polluted areas which may reduce their willingness to pay, since the extrinsic component of their children's survival probabilities ($\bar{\pi}_t$) is higher. We will come back to the role of different exposures to pollutants further below. If $\bar{c} = 0$ [item(ii)], the preferred tax rate would be the same for all agents unless agents are exposed to different degrees of pollution reflected by a different $\bar{\pi}_t$. Disregarded the existence of subsistence consumption, capital accumulation increases the preferred tax rate since it increases the pollution stock and thus the marginal benefit from taxation. On the other hand, human capital accumulation increases production but reduces the capital intensity of production. Since the latter overcompensates the former, the tax rate is declining in H_t [item (iii)].

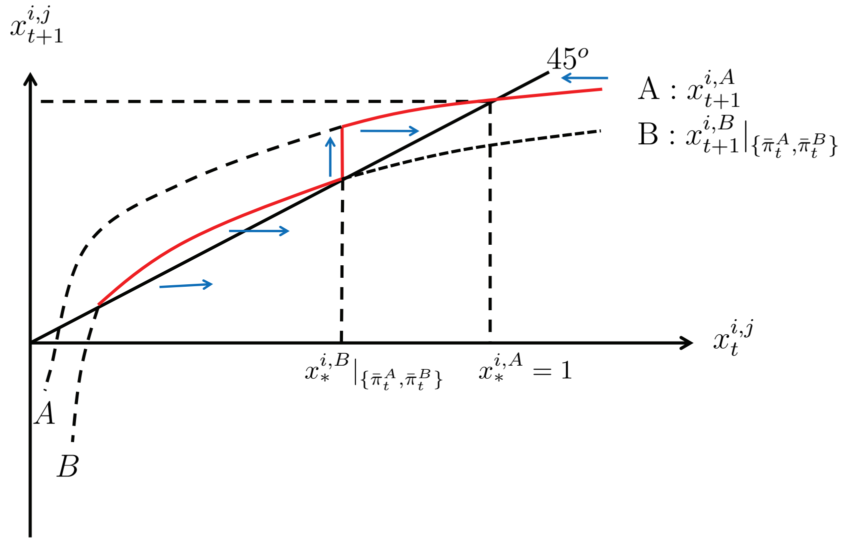

Figure 3: Evolution of relative human capital x_t^i. AA-locus: evolution of $x_t^{i,A}$. BB-locus: evolution of $x_t^{i,B}$ given $\{\bar{\pi}_t^A, \bar{\pi}_t^B\}$.

3. INEQUALITY AND REGIONAL SURVIVAL DIFFERENTIALS

We now allow for residential differences in the exposure to pollutants, for example due to differences in the residential proximity to emission sources. Consider a population that inhabits two areas denoted by A and B.

Lemma 2 (Residential differences in the exposure to pollutants)
Residents of region B are more exposed to pollutants stemming from the same emission sources than region-A agents, such that the extrinsic component of region A's children exceeds the one of region B's children, i.e. $\bar{\pi}_t^A > \bar{\pi}_t^B$.

The evolution of relative human capital (x_t^i) is decisive for individual decisions on child quality (see Lemma 1) and thus the evolution of individual incomes and inequality over time. Agents are allocated to region A or B according to their relative level of human capital (x_t^i): Agents with x_t^i above some threshold level $\tilde{x}^{crit}$ live in region A while type-B agents are characterized by $x_t^i \leq \tilde{x}^{crit}$.[15] The following proposition summarizes the evolution of relative human capital $x_t^{i,j}$ ($j = A, B$), in the two regions. The proof can be found in the Online Appendix.

[15]We thus abstract from migration decisions (endogenous residential sorting) from more to less polluted areas which would expand the structure of the model drastically without delivering further insights. The essential extension requires a lifetime utility arbitrage condition between region A and B and the explicit modeling of housing prices. Migration from B to A would increase housing prices there and establish a stopping rule of migration flows with wealthier households living in A. As lifetime utility depends then on the evolution of housing prices over the life cycle, the described approach is already close to intractability in much simpler OLG frameworks, see Grossmann et al. (2017). Accordingly, $\tilde{x}^{crit}$ is exogenous. In line with Roback (1982), differences in incomes across regions reflect differences in amenities associated with the chosen location.

Proposition 2 (Evolution of relative human capital in region A and B)

(i) Relative human capital of population group A, $x_t^{i,A}$, evolves according to

$$x_{t+1}^{i,A} = \left(\frac{zx_t^{i,A} - \varepsilon}{z - \varepsilon}\right)^{\eta} (x_t^{i,A})^{\nu}, \tag{24}$$

with a stationary and stable solution at $x_t^{i,A} = x_*^{i,A} = 1$ for all t and i for which $x_t^{i,A} > \tilde{x}^{crit}$.

(ii) Relative human capital of population group B, $x_t^{i,B}$, evolves according to

$$x_{t+1}^{i,B} = \left(\frac{zx_t^{i,B} - \varepsilon}{z - \varepsilon}\right)^{\eta} \left(\frac{1 - \beta\eta - \rho - \bar{\pi}_t^A}{1 - \beta\eta - \rho - \bar{\pi}_t^B}\right)^{\eta} (x_t^{i,B})^{\nu}, \tag{25}$$

where $x_t^{i,B} \leq \tilde{x}^{crit}$. Moreover,

(a) $x_{t+1}^{i,B}$ is affected by the extrinsic components of children's survival probability in the two regions, $\bar{\pi}_t^j, j = A, B$. Thus, there exists a stable conditional steady state $x_*^{i,B}|_{\{\bar{\pi}_t^A,\bar{\pi}_t^B\}}$ in each period, t.

(b) In light of Lemma 2, it follows that $\frac{1-\beta\eta-\rho-\bar{\pi}_t^A}{1-\beta\eta-\rho-\bar{\pi}_t^B} < 1$, such that the $x^{i,B}-$locus is below the $x^{i,A}-$locus and $x_*^{i,B}|_{\{\bar{\pi}_t^A,\bar{\pi}_t^B\}} < 1$.

(c) If the $\frac{\bar{\pi}_t^A}{\bar{\pi}_t^B}$ ratio shrinks (increases) during the transition towards $\frac{\bar{\pi}_*^A}{\bar{\pi}_*^B}$ with $\bar{\pi}_*^A > \bar{\pi}_*^B$, the $x^{i,B}-$ locus moves upwards (downwards), where $x_*^{i,B} < x_*^{i,A}$. If $\frac{\bar{\pi}_t^A}{\bar{\pi}_t^B}$ exceeds a critical threshold level, the B-locus is always below the 45-degree line and relative human capital endowments in region B approach zero within finite time.

We present the reasoning of Proposition 2 graphically in Figure 3. The evolution of $x_t^{i,j}$ ($j = A, B$) follows the A- or the B- locus, see (24) and (25). Both loci exhibit a stable steady state and, because of $\varepsilon > 0$, to the left of it an unstable steady state. In Figure 3, we fixed the threshold level of relative human capital ($\tilde{x}^{crit}$) to the conditional steady state of population group B, i.e $\tilde{x}^{crit} = x_*^{i,B}|_{\{\bar{\pi}_t^A,\bar{\pi}_t^B\}}$, such that the evolution of relative human capital follows the solid gray line.[16] The location of the B-locus is conditional on the state of the extrinsic components of children's survival probabilities as indicated by the subscripts $\bar{\pi}_t^j$, which are constant in the long run. Thus, the location of the B-locus is time varying during the transition to the steady state while the location of the A-locus is constant from the beginning. In light of Lemma 2 and Proposition 2, item (ii,b), the B-locus is always below the A-locus. If $\frac{\bar{\pi}_t^A}{\bar{\pi}_t^B}$ declines (increases) during the transition, the B-locus moves upwards (downwards) and the extrinsic survival component of children living in region B catches up (declines) relative to region A. If the B-locus moves downwards or is already relatively low due to a large difference in $\bar{\pi}_t^A$ and $\bar{\pi}_t^B$, the B-locus may be located below the 45-degree line such that relative human capital of this population

[16]The assumption that agents with average human capital live in region A is not harmful: if they were allocated to the B-region, $x_t^{i,B}$ would evolve according to (24) and $x_t^{i,A}$ would then be positively influenced by the survival differential between the A and the B region. Moreover, note that the region to the left of the unstable steady state is empirically irrelevant since it exceeds the maximal possible number of children over the life course by far.

group would approach zero within finite time.
Given Lemma 1 and 2, type-B agents exhibit a higher fertility and lower investments in education per child. Furthermore, the forces of the quality quantity trade-off are amplified via a relatively level of human capital, i.e. $x_t^{i,B} < 1$. Therefore, relative human capital $x_t^{i,B}$ is evolving at a slower pace over time compared to region A. Moreover, in the long-run, agents of region B will converge to a lower relative human capital stock compared to region-A agents, i.e. $x_*^{i,B} < x_*^{i,A} = 1$ [see Proposition 2, item (ii)].
Differences in $\bar{\pi}_*^j$ between the two regions are responsible for long-run differences in relative human capital endowments. This implication holds even though children's survival probabilities ($\pi_t^{i,j}$) may approach one. If the B-locus is increasing during the transition, survival probabilities are equal to 1 in both regions within finite time. Nevertheless, differences in $\bar{\pi}_t^j$ persist and translate into different expenditures on child quality affecting the growth performance of the economy. Hence, environmental conditions translate into parental decisions to invest in child quality although survival probabilities are high. This explains the significant but less pronounced link between exposure to pollutants and birth outcomes in developed countries today. Moreover, $\bar{\pi}_t^j$ affects the willingness to pay for tax-financed abatement measures.

Proposition 3 (Effect of $\bar{\pi}_t^j$ on the preferred tax rate)
The preferred tax rate of a pivotal agent $\tau_t^{p,j}$ in region $j = A, B$, is inversely related to the extrinsic component of children's survival probability, $\bar{\pi}_t^j$, i.e.

$$\frac{\partial \tau_t^p}{\partial \bar{\pi}_t^j} < 0, \tag{26}$$

given the sufficient condition

$$\frac{1 + \gamma(\bar{\pi}_t^j + \rho)}{b_3 \mu} y_t^p \frac{H_t}{Y_t} > \bar{c}. \tag{27}$$

For the proof, see the Online-Appendix.
The last proposition states that the pivotal agent's willingness to pay for tax-financed abatement measures is inversely related to the external survival component of children's probability to survive childhood given that her income (y_t^p) is sufficiently high, i.e. (27) is fulfilled. As $\bar{\pi}_t^j$ as well as $\frac{H_t}{Y_t}$ are constant in the long-run but incomes continue to grow, condition (27) and $\frac{\partial \tau_t^p}{\partial \bar{\pi}_t^j} < 0$ will hold for all income classes within finite time. Nevertheless, owed to the hierarchy of needs, richer agents may prefer a higher tax rate although they are less exposed to pollutants (see item (i) of Proposition 1). Whether or not this is the case depends on the magnitude of $\frac{\partial \tau_t^p}{\partial \bar{\pi}_t^j}$ compared to $\frac{\partial \tau_t^p}{\partial y_t^p}$ and thus on the level of $y_t^p$and $\bar{\pi}_t^j$. Propositions 1 and 3 have interesting policy implications: high inequality implies that the pivotal agent of a democracy (median voter) would be a region-B agent. This agent would prefer zero taxes if his income falls below the critical income level ($\tilde{y}$) as defined by Proposition 1, while a richer region-A agent may prefer a positive tax rate. Thus, during the transition, full democratization may be harmful for the environment and human capital accumulation, if inequality is comparatively high and the median voter relatively poor, unless democratization is accompanied by redistribution schemes.

4. NUMERICAL EXPERIMENTS

We now turn to numerical experiments in order to investigate (1) the impact of inequality on the evolution of child mortality differentials. (2) We look at the impact of pollution on inequality and finally we explore the consequences of different levels of preferred abatement measures on the evolution on mortality differentials and inequality. Parameters of the model are set, such that the balanced growth path of the model fits to empirical observations of the US economy and United Nations long-run projections (de la Croix and Doepke 2003,2004; Strulik 2004,2008; Schaefer, 2014). A sketch of the numerical method, a discussion of the parameters, as well as further details about the equilibrium can be found in the Online-Appendix.

(1) Increase in initial inequality

As $\bar{\pi}_t^A > \bar{\pi}_t^B$, population groups converge to different steady states characterized by $x_*^A = 1 > x_*^B$ (see Propositon 2). Lower relative human capital endowments and $\bar{\pi}_t^A > \bar{\pi}_t^B$ imply that type-B agents invest less in child quality, face higher child mortality rates and exhibit a higher number of births compared to type-A agents. Consequently, income inequality and the mortality differential between region B and A expressed as $(1 - \pi_t^B) - (1 - \pi_t^A) = \pi_t^A - \pi_t^B$ increases. As incomes grow also poorer households increase their expenditures on health and nutrition, such that reinforced by the adoption of tax-financed abatement measures mortality differentials begin to shrink. This process is mirrored by a hump-shaped evolution of pollutants owed to a higher willingness to support tax-financed abatement measures. Reduced child mortality rates leave, on the other hand, more space for expenditures on child quality, such that the population's growth rate peaks. Now the incomes of poorer households experience higher growth rates and the evolution of income inequality follows also a Kuznets curve .[17] Thus our model is able to trace the hump-shaped evolution of mortality differentials between regions characterized by different degrees of environmental degradation as it has been illustrated by Figure 1 (see solid lines in Figure 4).

[17] Historical values of the Gini coefficient for the UK can be found in Milanovic et al. (2010) and Cribb (2013): 45.9 (1759), 51.2 (1801), 57.7 (1867), 52 (1880), 25 (1979), 36 (2007).

a) mortality differential b) pollution c) Gini (income)

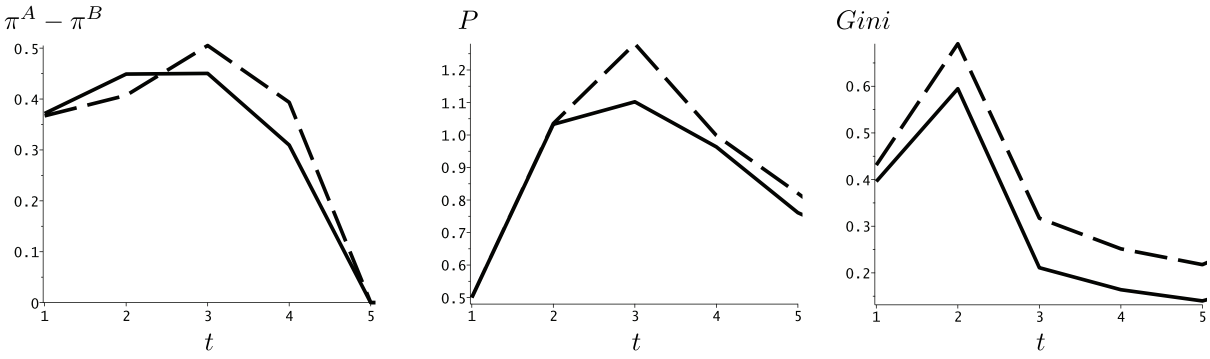

Figure 4: Baseline scenario: solid line; higher initial inequality: dashed line.

Higher initial inequality in human capital (dashed lines in Figure 4) implies that more households are living in region B,[18] such that more households are subject to $\bar{\pi}_t^B < \bar{\pi}_t^A$ and a reduced x_t^i. Consequently, more households face lower survival probabilities of their children and devote less of their incomes to expenditures on child quality. Initially, mortality differentials may fall short of the baseline scenario because of lower levels of production. Associated lower income growth rates reduce expenditures on children's health and nutrition, such that the peak of the mortality differential is delayed.[19] Less abatement implies that pollutants peak at a higher level while slower income growth and lower average expenditures on child quality imply a higher peak in the Gini coefficient. Long-run inequality increases as well because more households are exposed to a higher pollution level which reduces their willingness to pay for child quality but increases their desired family size. Thus, higher initial inequality increases the mortality differential between both regions and reduces long-run growth.

(2) Pollution and inequality

a) Higher initial pollution ($P_0 \uparrow$) - Both regions are adversely affected by the increase in pollutants, but region A is less exposed compared to B. Hence, $\bar{\pi}_t^A$ is reduced relative to $\bar{\pi}_t^B$ by a lower extend, such that mortality differentials increase (see Figure 5). A smaller extrinsic component of children's survival probabilities in both regions reduces expenditures on child quality. Thus, income inequality falls short of the baseline scenario. These effects are transitory only, because the economy converges to the same steady state.

[18] We keep the mean of the initial distribution constant.

[19] For higher initial inequality or higher adverse impacts of production on pollution, mortality differentials exceed also the initial levels of the baseline scenario.

a) mortality differential b) pollution c) Gini (income)

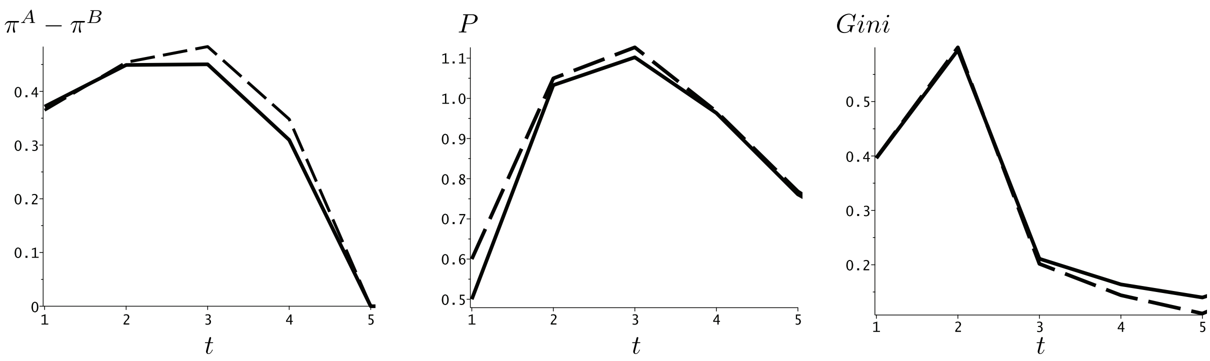

Figure 5: Baseline scenario: solid line; higher initial pollution: dashed (dotted) line.

b) Higher adverse impact of production on the environment (b_2 ↑) **-** The marginal benefit of tax-financed abatement measures shrinks, such that the preferred tax rate is reduced. Hence, the level of pollutants increases (see Figure 6) which adversely affects the extrinsic component of children's survival probability. Since region-B agents face a higher exposure to pollutants compared to region-A agents, $\bar{\pi}^B$ experiences a stronger reduction than $\bar{\pi}^A$ and mortality differentials increase compared to the reference scenario.

a) mortality differential b) pollution c) Gini (income)

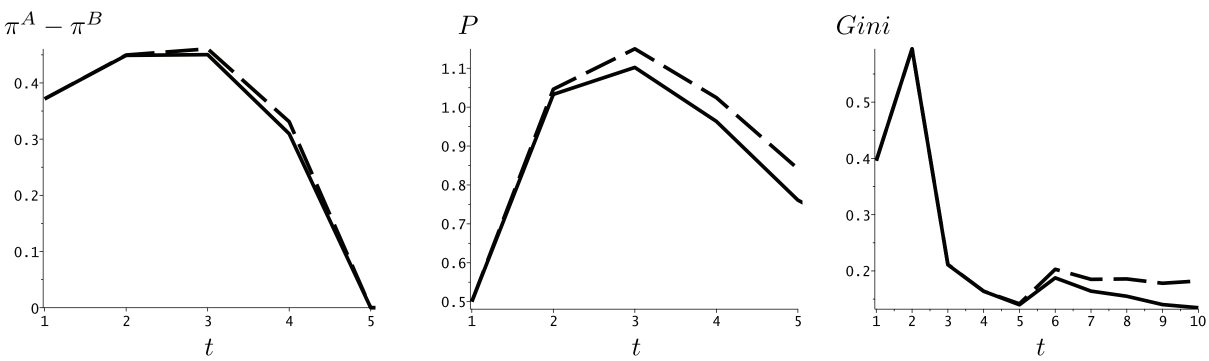

Figure 6: Baseline scenario: solid line; higher impact of pollution: b_2 +10% dashed line.

The asymmetric reduction in the extrinsic component of children's survival probability translates into a stronger reduction in expenditures for children's education in region B, such that inequality rises, population growth increases and economic growth is reduced.[20]

(3) Different taxes

[20] The case of higher (lower) exposure to pollutants in B (A) is similar and can found in the Online-Appendix.

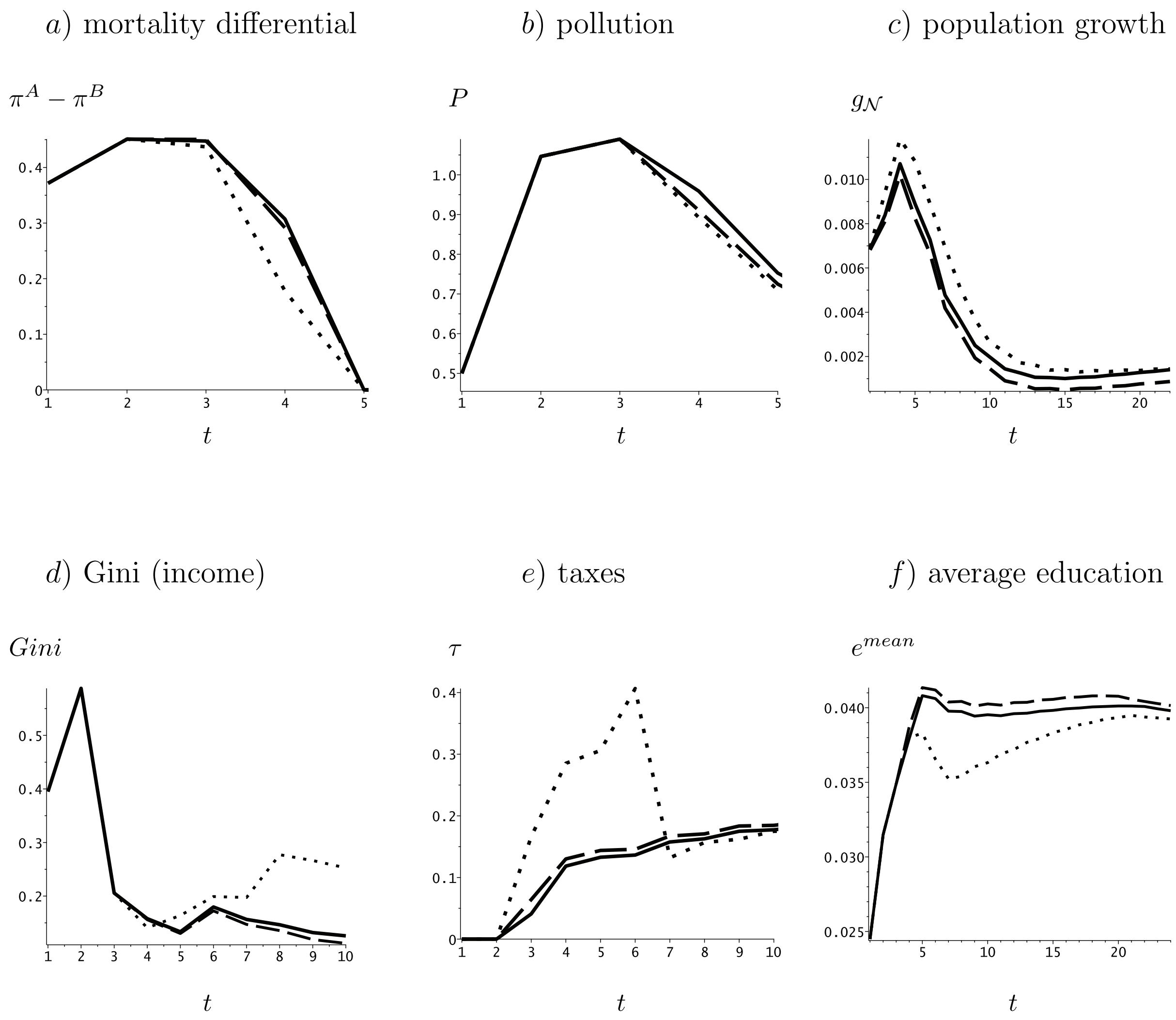

Figure 7: τ_t^A is implemented: solid line; τ_t^B is implemented: dashed line; A finances the preferred abatement level of B until $t = 7$ then regime switch to τ_t^B: dotted line.

a) Population group B is pivotal - Region-B agents are poorer but more exposed to pollutants, such that their preferred tax may exceed τ_t^A (see Figure 7). Higher abatement reduces pollution and the mortality differentials between both regions. As the gap between the extrinsic survival components is reduced, parents in region B increase their expenditures on children's education relative to region A, such that income inequality is reduced.

b) Progressive taxation and group B is pivotal - Region-B's preferred amount of abatement is financed by population group A. This reduces available incomes there but increases incomes in region B. Hence, the mortality differentials between the two regions are further reduced. On the other hand, population growth increases because of higher available incomes and higher survival probabilities in region B. As a consequence production grows at a lower rate, such that the level of pollutants is (slightly) lower as well. Income inequality is initially reduced, but mainly because average expenditures on education have shrunk. As soon as mortality differentials begin to close, the reduced expenditures on education in B induce an increase in income inequality above the reference scenario. As growing incomes increase the preference for abatement, the tax burden for the richer agents continues to rise hampering their capital accumulation and labour supply which adversely affects the wage rate and lifetime utility of all agents. Thus, lifetime utility in this tax regime may fall short of the level obtained under a), such that in later stages of economic development population group B would prefer to switch to regime a) rather than passing on their preferred level of abatement to the rich. As the economy switches to a) and τ_t^B is implemented, the tax falls short of the level obtained in a) because of a lower pollution level and converges from below to its steady state level. The economy converges now with increasing average expenditures on eduction and declining population growth towards the steady state obtained in a). The boost in expenditures on education increases inequality further and overshoots during the transition the corresponding level of the baseline scenario. Note that we assumed a very progressive taxation scheme in the sense that B contributes nothing and A everything. A milder scheme would allow for a lower degree of progression rather than switching to regime a), but the qualitative results would remain intact. Moreover, the timing of the regime switch depends on how rich population group B compared to A is and thus on inequality. Higher inequality delays the regime switch.

5. SUMMARY AND CONCLUSIONS

We argued that the transition from high child mortality rates to increasing investments in education, low fertility and low mortality rates required the establishment of tax-financed abatement measures aimed at an attenuation of the adverse effects of production on children's health. Agents' willingness to support this policies in turn is predominantly driven by their exposure to pollutants and their disposable incomes. Therefore, inequality matters along two dimensions: (1) richer households tend to spent more on child quality and (2) are due to a greater residential distance to emission sources less exposed to pollutants.

Higher incomes increase the willingness to pay for tax-financed abatement measures but a lower exposure to pollutants reduces it. This mechanism implies, on the other hand, that poorer households being more exposed to pollutants may prefer a lower level of abatement compared to the rich if their income is sufficiently low. In the long-run, the preferred tax rate is increasing in the exposure to pollutants and poorer households may prefer a higher level of abatement than richer households. If this is the case, the adverse effect of pollution on health is highest, if political institutions are biased towards the rich because the least affected population group prefers the lowest level of tax-financed abatement measures. Political reforms are indicated under this circumstances because economic inequality interacts with social segregation and political inequalities implying differentials in health (Deaton, 2003; Alesina, Baqir, and Easterly, 1999). Szreter and Mooney(1998) argued that the key to understanding the mortality transition in England lies in local politics. Only after political reform (Reform Acts), political inequality (and potentially income inequality) was reduced, and issues as sanitation, public health and the fragile onset of abatement measures in the production sector became topics of high(er) priority in the agendas of (local) policies.

The described mechanisms provide a candidate explanation for: (1) the hump-shaped evolution of child mortality ratios between areas that are subject to different degrees of environmental pollution, and (2) The observed positive cross-country correlation between economic inequality and pollution at the local level.

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